Early History of the Carthage-Colton Shear Zone, Grenville Province, Northwest Adirondacks, New York (U.S.A.)

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ABSTRACT

The Adirondack Mountains expose two distinct tectonic elements of the Proterozoic Grenville Province of northeastern North America: the Adirondack Lowlands and Highlands. The Lowlands are located along the eastern edge of the Metasedimentary Belt, and the Highlands form the western portion of the Granulite Terrane. The two are separated by the Carthage-Colton Shear Zone (CCSZ). U/Pb titanite and ^{40}Ar-^{39}Ar hornblende ages in the Lowlands are ca. 100 m.yr. older than in the Highlands, across the CCSZ. While both the Lowlands and the Highlands record a history of metamorphism during the Elzevirian Orogeny (ca. 1150 Ma), only the Highlands record evidence of a major phase of Grenvillian thermotectonic activity (Ottawan Orogeny) at ca. 1090–1030 Ma. Proposed tectonic models require that the Lowlands were either laterally separated from the Highlands or were at structurally higher levels during this metamorphism. New U/Pb and ^{40}Ar-^{39}Ar ages from titanite and hornblende-bearing mylonites in the Dana Hill metagabbro within the CCSZ constrain the timing of early shearing and offer a possible solution explaining the discrepancy in metamorphic ages between the Highlands and Lowlands. Precise U/Pb titanite ages at 1020 Ma are coupled with ^{40}Ar-^{39}Ar hornblende ages at 1000 Ma within the shear zone. Thermobarometric constraints indicate that deformation occurred under granulite-facies conditions. Therefore, titanite and hornblende ages are interpreted as cooling ages from a ca. 1050–1030-Ma event. An early transpressive shearing event at ca. 1040 Ma, combined with structural data in the Dana Hill metagabbro that indicate strike-slip displacement along the CCSZ, suggests significant lateral displacement between the Lowlands and the Highlands during the ca. 1090–1030-Ma Ottawan Orogeny, prior to later extension along the CCSZ.

Introduction

The ca. 1.1-Ga Grenville Orogen of northeastern North America exposes substantial parts of an ancient orogenic belt, which creates an opportunity for the study of the evolution of ancient mountain systems. Understanding the style and timing of deformational events during these times has important implications for models of both the formation of Rodinia and its subsequent breakup. The Grenville Province in northeastern North America is a laterally continuous (from Labrador to southern Ontario) region composed of high-grade, polymetamorphic terranes that are separated from one another by ductile shear zones (fig. 1). The continuous exposure of the Grenville-aged rocks in this area, as opposed to patchy exposures along the southeastern coast of the United States, the Llano uplift in Texas, and outcrops in Mexico, provides an opportunity to study large-scale features that are now well exposed but were once the root of an ancient orogen. A comprehensive database of geochronologic, petrologic, and structural information documents the timing and nature of major metamorphic and deformational events throughout the history of the orogen. The Grenville Province represents an area of repeated episodes of high-grade deformation and metamorphism in which shear zones appear to have been multiply active (e.g., Davidson 1998). Therefore, although there is excellent continuous exposure of mid-crustal levels of the Grenville Orogeny in northeastern North America, it has been difficult to develop complete tectonic scenarios that accurately describe the evolution of the region. Most studies focus on the development of the orogen and how it may compare with the

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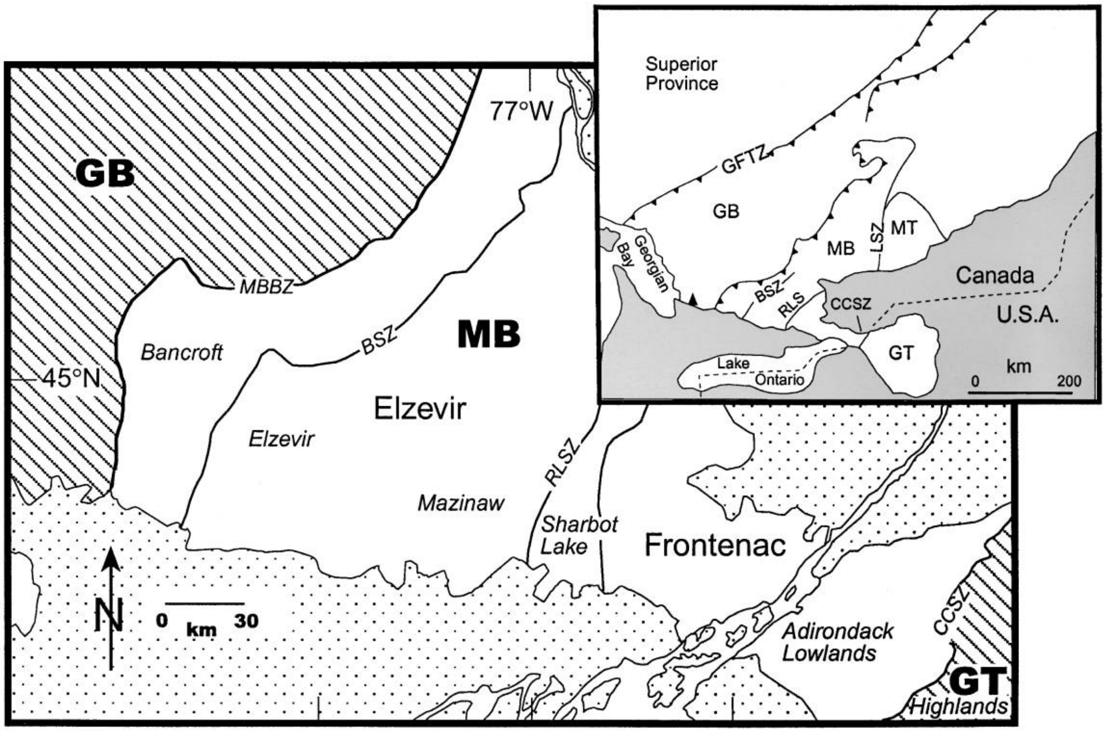

Figure 1. Generalized map of the Metasedimentary Belt (inset shows generalized map of the Grenville Province). *GB*, Gneiss Belt; *MB*, Metasedimentary Belt; *GT*, Granulite Terrane; *MT*, Morin Terrane (*inset*); *GFTZ*, Grenville Front Tectonic Zone (*inset*); *MBBZ*, Metasedimentary Belt Boundary Zone; *BSZ*, Bancroft Shear Zone; *RLSZ*, Robertson Lake Shear Zone; *CCSZ*, Carthage-Colton Shear Zone; *LSZ*, Labelle Shear Zone (*inset*); Elzevir terrane comprises Bancroft, Elzevir, and Mazinaw domains.

evolution of more recent mountain belts (Windley 1986; McLelland et al. 1996; Wasteneys et al. 1999; Hanmer et al. 2000). Central to these studies is the analysis of major, crustal scale shear zones along which most of the deformation in the Grenville Orogeny is partitioned. Many of these shear zones have apparently been active more than once and how they link to the present-day expression of the province is key to understanding the tectonic evolution of the region.

The southwestern segment of the Grenville Province is subdivided into belts separated by ductile shear zones (Davidson 1986; fig. 1). An autochthonous belt to the west (present-day coordinates) is largely composed of reworked Archean and Paleoproterozoic rocks that can be correlated with the Laurentian craton (Rivers et al. 1989; DeWolf and Mezger 1994). Farther to the east, the allochthonous belts represent accreted packages of rock that have been transported and cannot be directly correlated with the edge of the Laurentia. The autochthonous belt has been termed the "Gneiss Belt" (GB) (following a slightly modified version of the nomenclature of Wynne-Edwards [1972]); the Metasedimentary Belt (MB) and Granulite Terrane (GT) comprise the allochthonous belts. Ductile shear zones separating these belts are the Metasedimentary Belt Boundary Zone (MBBZ) (separating the GB and the MB) and the Carthage-Colton Shear Zone (separating the MB and the GT, fig. 1; Wynne-Edwards 1972; Easton 1992). In addition, several major, ductile-to-brittle shear zones separate distinct domains within both the MB and GB (Davidson 1986; Hanmer 1988; Mezger et al. 1991*b*; Easton 1992; Busch et al. 1996; fig. 1). Some domains have distinct ages of metamorphism as well as late offsets across extensional zones that lead to differences in unroofing ages across the MB (e.g., Cosca et al. 1992, 1995; van der Pluijm et al. 1994). The Elzevir terrane (comprising the Bancroft, Elzevir, and Mazinaw domains, after Easton [1992]; fig. 2) shows similar ages of metamorphism across domain boundaries, as documented by the U/Pb analyses of titanite (Mezger et al. 1991*b*, 1993). However, strikingly different ^{40}Ar-^{39}Ar ages of hornblendes across shear zones in the terrane indicate

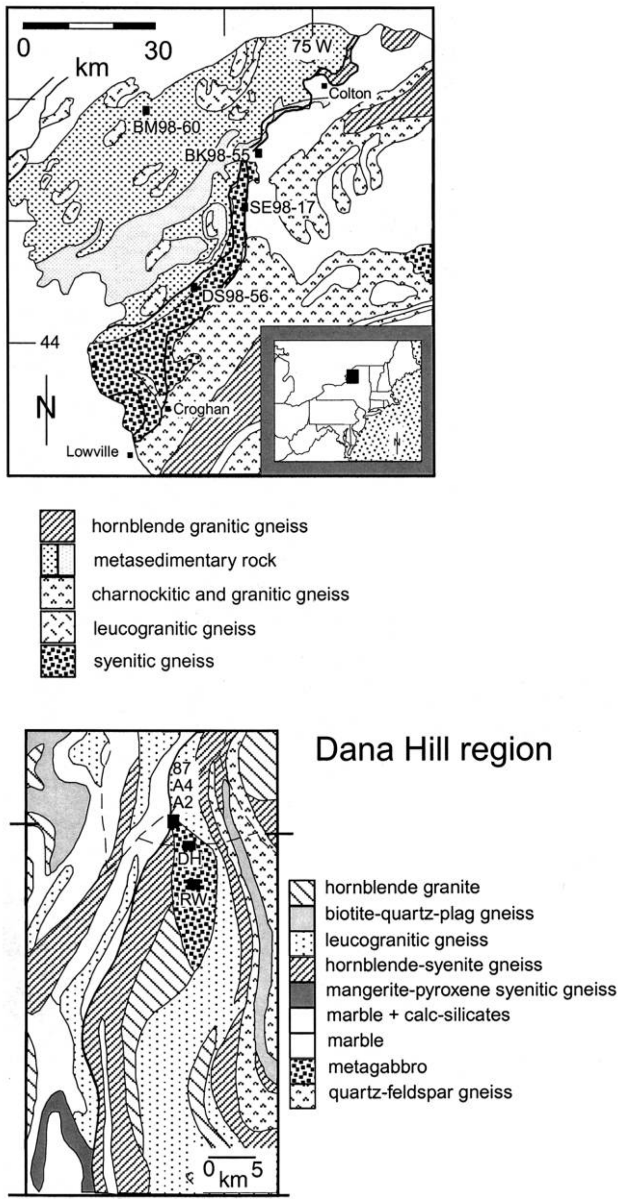

Figure 2. Map of the Adirondack region with detailed map showing the position of the Dana Hill body. Heavy black lines indicate the mapped Carthage-Colton Shear Zone. Sample locations and outcrops are indicated on both maps, and major lithologies are indicated.

an episode of late extension in the region (Cosca et al. 1992). There are also significant differences in the ages of metamorphism across some shear zones, such as the Carthage-Colton Shear Zone (CCSZ), which separates the Adirondack Lowlands (metamorphic titanite ages of ca. 1160 Ma) from the Adirondack Highlands (metamorphic titanite ages of ca. 1050 Ma; Mezger et al. 1991*b*, 1992; fig. 2). However, neither pressure-temperature conditions nor lithologies are drastically different across this boundary leading to considerable controversy regarding the nature and significance of the CCSZ (Wiener et al. 1984; Bohlen et al. 1985; McLelland et al. 1996).

Current tectonic scenarios for the Grenville Province in southern Ontario describe a series of arc-continent to continent-continent collisions between 1.3 and 1.0 Ga (e.g., McLelland et al. 1996; Rivers 1997; Wasteneys et al. 1999). Episodes of orogenesis clearly seem to combine with periods of crustal scale extension for reasons that are debated (van der Pluijm and Carlson 1989; Culshaw et al. 1994; McLelland et al. 1996). The MB can most easily be seen as a group of small terranes stitched together by plutons and sutured with ductile shear zones during the history of the orogen. The entire MB and the GT were affected by metamorphism and deformation at ca. 1160 Ma (McLelland et al. 1988; van Breemen and Davidson 1990; Mezger et al. 1991*b*, 1993; Chiarenzelli and McLelland 1993; Corfu and Easton 1995, 1997).

It is clear from thermobarometry and geochronology that the entire MB and GT were at similar *PT* conditions during this time (Anovitz and Essene 1990). McLelland et al. (1996), among others, postulate that the 1160-Ma event represents a major mountain-building orogeny and that subsequent mantle delamination may have led to the widespread, voluminous emplacement of anorthosite-mangerite-charnockite-granite (AMCG) magmas in the MB. The third orogen-scale deformation event in the Grenville Province is widely thought to be a continent-continent collision (the Ottawan Orogeny) at ca. 1090–1030 Ma (McLelland et al. 1996). The identity of this continent has not firmly been established; however, most workers agree that it is likely Amazonia (see recent Rodinia reconstructions by Weil et al. [1998]).

This event includes granulite-facies conditions at ca. 1050 Ma in the Adirondack Highlands leading some to postulate that the Adirondack Highlands were very close to the core of the Grenville Orogen (McLelland et al. 1996). However, directly to the west in the Frontenac/Adirondack Lowlands region, across the Carthage-Colton zone, there is no evidence of metamorphism at this time (Mezger et al. 1992). Extensive geochronology documents only the existence of the earlier ca. 1160-Ma metamorphism in these rocks. Farther to the west, in the Elzevir terrane, there is evidence of a ca. 1050-Ma metamorphism as documented by metamorphic titanite ages (Mezger et al. 1993). There is additional evidence of an Ottawan metamorphism and deformation in the GB even farther to the west (e.g., Culshaw et al. 1994; Davidson 1998). The absence of Ottawan deformation in the Frontenac/Lowlands region has been puzzling, and many attempts have been made to explain the discrepancy. Some studies have proposed a vertical displacement between the Frontenac/Lowlands and the rest of the MB and GT (e.g., McLelland et al. 1996). These studies argue that the Lowlands block was simply at a higher crustal level than the adjacent regions in the MB and therefore escaped high-grade metamorphism and deformation. It is likely that all these terranes were at a similar level during the culminating Elzevirian Orogeny at ca. 1160 Ma; this would require multiple shearing events along the zones that bound the Frontenac/Lowlands. In this scenario, the Frontenac/Lowlands block would be thrust over the rest of the MB in the northwest and the GT in the southeast at some time after the 1160-Ma metamorphism and then juxtaposed at its current structural level sometime after the Ottawan deformation.

It has been proposed that the Carthage-Colton zone, separating the Lowlands and the Highlands, represents the trace of such a multiply active boundary (McLelland et al. 1996). Mezger et al. (1992) favored another scenario in which the Lowlands region escaped Ottawan metamorphism and deformation by being laterally separated from the Highlands via a small ocean basin, or the two segments were brought into their current position by later strike-slip faulting. The rifting event would have occurred after the ca. 1160-Ma metamorphism and then final suturing along the present-day CCSZ would have juxtaposed the Highlands and Lowlands into their current configuration sometime after the ca. 1050-Ma Ottawan Orogeny. Previous studies show that there must have been late, post-orogenic extension across the zone at ca. 930 Ma (Streepey et al. 2000); but its earlier history remains obscure. The purpose of this contribution is to elucidate this earlier history of the CCSZ to clarify the evolution of the eastern portion of the North American Grenville Province in New York.

Geologic Setting

The Adirondack Lowlands are primarily a series of carbonates and siliciclastic sediments that were metamorphosed to upper amphibolite-facies conditions. Foliations in gneisses generally dip shallowly to the northwest with mineral lineations plunging in the down-dip direction. Metamorphic pressures and temperatures have been well determined in this region and the age of peak *PT* conditions has been dated at ca. 1150 Ma (McLelland et al. 1988; Chiarenzelli and McLelland 1991; Mezger et al. 1991*a*, 1993). This coincides with the timing of the Elzevirian Orogeny, the first part of what is known as the Grenville orogenic cycle (Moore and Thompson 1980).

The Adirondack Highlands, separated from the Lowlands by the CCSZ, consist of primarily meta-igneous rocks metamorphosed to granulite-facies conditions. Metamorphic ages, determined by U-Pb dating of titanite, zircon, and monazite, show that peak, granulite-facies *PT* conditions were obtained at ca. 1050 Ma, 100 m.yr. after peak conditions were reached in the Lowlands (Mezger et al. 1991*b*, 1992). However the difference in lithologies and *PT* conditions across the boundary is indistinct (Bohlen et al. 1985). This has led to conflicting reports on the nature of the shear zone, in which many workers have argued that the CCSZ does not represent a tectonically significant boundary (e.g., Geraghty et al. 1981; Bohlen et al. 1985). The striking difference in metamorphic ages precludes the idea that the CCSZ is an insignificant feature although the geologic similarities between the Highlands and the Lowlands need to be explained. The Diana syenite represents perhaps the most obvious example of this problem. Well-preserved contact aureoles from the Diana are seen in the Adirondack Lowlands (Powers and Bohlen 1985); however, the Diana syenite bears a lithologic similarity to the Stark complex in the Adirondack Highlands. On the basis of the contact aureoles, it seems logical to link it to the Adirondack Lowlands and draw the trace of the CCSZ along its eastern edge (Mezger et al. 1992), but the lithologic similarity to the Highlands makes this a tenuous choice.

The CCSZ itself is a poorly exposed zone of concentrated shear that is meters to kilometers wide. Shear sense indicators can be conflicting, and this has also added to the debate over the significance of this boundary (Hall 1984). Most mylonitic foliation in the CCSZ dips to the northwest and a slight majority of shear sense indicators suggest a northwest-side-down sense of motion, although there are indicators that are suggestive of a displacement in the reverse direction. Geochronologic studies when combined with the structural information show that the CCSZ must have undergone a normal sense of displacement in order to juxtapose the Lowlands and the Highlands at their current structural levels.

Dated minerals such as zircon, monazite, titanite, hornblende, and biotite have provided nearly complete temperature-time histories for both the Adirondack Highlands and Lowlands (Mezger et al. 1991*b*, 1992, 1993; Streepey et al. 2000). By this method, the age of shearing across the CCSZ is only indirectly known, since it must be calculated by the difference in metamorphic and cooling ages from rocks on either side of the zone. It is known from previous studies that the CCSZ was last active around ca. 930 Ma from differences in hornblende and biotite ^{40}Ar-^{39}Ar ages in the Highlands and Lowlands (Streepey et al. 2000). However, minerals that can be shown to have grown in the CCSZ during shearing have never been dated. This article presents results from a suite of titanites, dated by the U/Pb method, and hornblendes, dated by the ^{40}Ar-^{39}Ar technique, that have grown within the CCSZ. These minerals are from a variably mylonitized body in the middle of the CCSZ, the Dana Hill metagabbro. Dating these minerals directly provides time constraints for shearing in this region and constrains the history of motion across this tectonic boundary.

The Dana Hill body (DHB) is located north of Edwards, New York, in the vicinity of the mapped CCSZ (fig. 2). The body is exposed primarily along Dana Hill Road (see map), and it also forms large knobs on the east and west sides of Route 87 north of Edwards. The DHB grades locally from a strongly mylonitized texture to an igneous, cumulate texture in some areas with several small-scale, crosscutting shear zones forming an anastamosing network in outcrop. In addition, the body is characterized by abundant amphibole and tourmaline veins. Shear zones commonly exhibit upper-amphibolite to granulite-facies assemblages composed of amphiboles with pyroxene cores, hornblende, biotite, titanite, and plagioclase (Johnson et al. 2000).

Four major outcrops of the DHB are in this area, and they were mapped in detail and sampled for this project. In each outcrop, samples were taken from crosscutting shear zones, as well as abundant amphibole veins, breccias, rocks with undeformed textures, and laterally continuous areas of mylonites. Outcrops 87 and A4 mark the exposed northwest tip of the DHB (fig. 2). These outcrops are knob forming and most of them are exposed as a rounded "pavement" outcrop. Figure 3 shows typical textures from these outcrops. Abundant centimeter-scale small shears that grade into coarser textures with amphibole knots are typical (fig. 3*a*). These small shears are often anastamosing but can also be regularly spaced and trend parallel or subparallel (fig. 3*b*). Textures range from undeformed to a strong tectonic fabric cut by abundant amphibole veins (fig. 3*c*, 3*d*). Veins are present in a wide range of orientations; many crosscut one another, but just as often follow a strong fabric, as shown in figure 3*d*. Samples were collected from as many different fabrics as possible, in order to analyze systematically both the petrology and the geochronology and to characterize any discrete events that may have influenced the fabric development of the DHB. Table 1 details the textural significance as well as the general petrologic assemblages found in the samples taken from the DHB.

In addition to petrologic studies, abundant structural measurements were taken in the body. The foliation trends north-northwest and has a near-vertical dip. Small shears also maintain this orientation. Stretching lineations are commonly horizontal or subhorizontal, plunging at 20°–30° and trending subparallel to the strike of the foliation at N50W (fig. 4). The exposed northern contact of the DHB is sharp and occurs at the north end of outcrop 87. Southern contacts are poorly exposed and therefore not well defined. Titanite and hornblende samples were collected throughout the DHB; care was taken to distinguish the fabric of each sample in an attempt to correlate veins, small shears, and major mylonitic fabrics with the timing of shearing along the CCSZ.

Analytical Techniques

Hornblendes. Hornblende grains were separated from 14 different drill cores and hand samples of the DHB. These comprised a variety of crosscutting fabrics. Samples were collected from a major mylonite fabric, several crosscutting smaller shears, pure amphibole veins, and from apparently undeformed regions of the DHB. Hornblendes were crushed, sieved, purified magnetically when necessary, and handpicked under a binocular microscope. Grain size of analyzed hornblendes varied as a function of deformation, but grains generally were 100–500 μm and were analyzed as single crystals. Hornblende samples were irradiated at the University of Michigan Ford Phoenix reactor for 120 h in the L67 core location. The standard MMhb-1 (age 520.4 Ma; Samson and Alexander 1987) was also irradiated and measured to calculate neutron flux in the reactor. All hornblende samples were analyzed at the University of Michigan Radiogenic Isotope Geology Laboratory. Hornblendes were step heated until fusion using an argon-ion laser and analyzed on a VG1200 mass spectrometer. Individual steps were heated for 60 s with a defocused beam followed by 2 min of gas purification using two 10 1/s SAES getters (ST101 alloy) and a liquid N_2 cold finger. Ages were calculated using the decay constants defined by Steiger and Jäger (1977). Plateaus were defined by 50% or more of the total ^{39}Ar released in three or more consecutive steps and

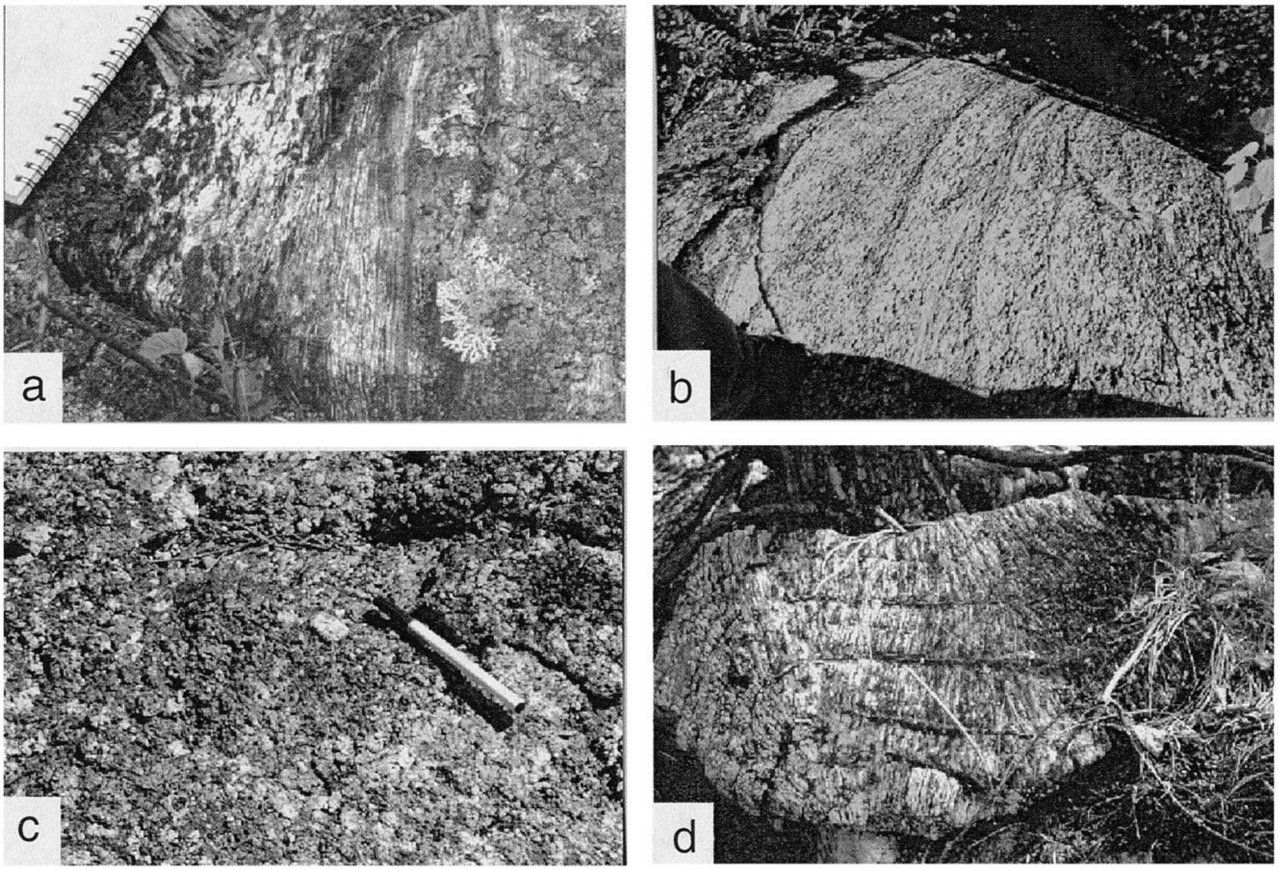

Figure 3. Field photographs of Dana Hill metagabbro, showing major fabrics in the body. *a*, Photograph of outcrop A4. Major mylonite grades into coarser gneissic fabric with clots of hornblende. Foliation strikes 140° with nearly vertical dip. Sample CR-6A4 is from one of the hornblende clots. *b*, "Pavement" outcrop showing network of small shears from the DH outcrop. Photograph taken looking south-southeast. *c*, Outcrop A4 shows nearly undeformed textures, with cumulus plagioclase grains. Sample CR9-A4 represents this fabric. *d*, Fabric in outcrop 87, with mylonitized Dana Hill cut by subparallel, folded hornblende veins.

by overlap of the ages of the steps at the 2σ confidence level. Plateau ages were calculated as the inverse variance weighted mean of ages from the steps in the plateau. Duplicates, and occasionally triplicates, were run on all samples to ensure results and check grain-to-grain variability in ages.

Titanite. Titanite grains were separated from samples of several crosscutting shear zones in the DHB as well as from samples from the Diana syenite, the Adirondack Lowlands, and the Adirondack Highlands. Every sample analyzed by the ^{40}Ar-^{39}Ar method was examined for titanite. All titanite-bearing samples were analyzed to obtain as many titanite/hornblende pairs from the same sample as possible. Samples containing fine-grained titanite were crushed and sieved. Sieved fractions of 500–250 μm were magnetically separated using a Frantz Isodynamic separator, and nonmagnetic fractions were further purified using the heavy liquid bromoform. This resulted in a fraction with a high concentration of titanite. Individual titanite grains were handpicked under a binocular microscope and grains with visible inclusions were avoided. Darker-colored titanites were analyzed when possible, but most titanite grains in the DHB are characterized by a light-brown cinnamon color.

Pure titanite separates were washed for 20 min in warm 2 N HCl to remove any surface contamination. Titanite grains were then spiked with a mixed $^{205}Pb/^{233}U$ tracer before dissolution. Titanites were dissolved in 3-mL Teflon vials in Krogh-style bombs after the method of Parrish et al. (1987). After 36–48 h in a solution of concentrated HF and HNO_3 at 180°C, titanites were decomposed. Samples were evaporated and 6 M HCl was added to dissolve any fluorite. Samples were dried and titanites were then completely soluble in 3 N HCl. Using Biorad 1-X8 resin, Pb and U were separated using HCl-HBr and $HCl-HNO_3$ column chemistry, respectively. Pb and U were loaded onto Re-filaments using the phosphoric acid–silica gel technique (after Cameron et al. 1967).

All titanite analyses were carried out in the Zentrallabor für Geochronologie at the University of Münster, Germany, using a VG Sector 54 multicollector mass spectrometer. Most isotopes were analyzed with Faraday collectors; however, ^{204}Pb was analyzed with a Daly detector ion-counting system. The standards NBS982 (for Pb) and U500 (for U) were used to calculate the isotopic fractionation factor, which was then applied to U and Pb sample analyses. The calculated fractionation factor for U was 0.11% and for Pb it was 0.13%. Duplicates of all titanite samples were analyzed and all results were reproduced.

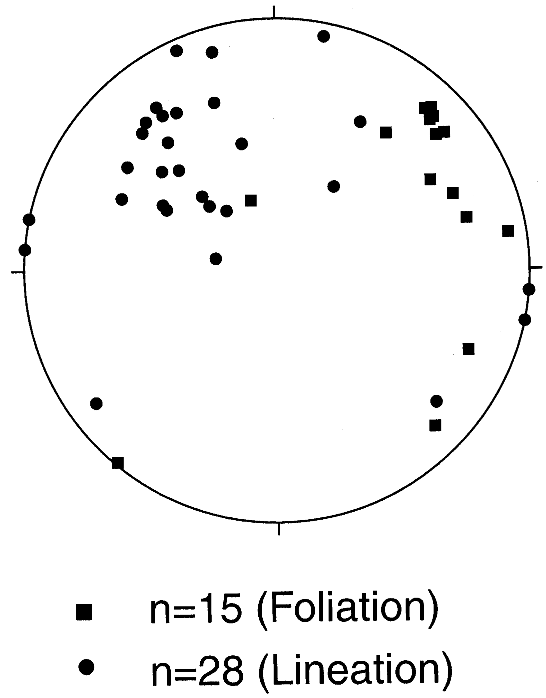

Figure 4. Foliation and lineation measurements taken within the Dana Hill metagabbro. Lineations trend to the northwest and are subhorizontal or plunge shallowly. Associated foliation strikes to the northwest and dips steeply to the west (poles to foliation plotted).

Results

Hornblendes. Analyzed hornblendes are generally characterized by even ^{39}Ar release patterns resulting in clean plateaus for most of the samples. ^{40}Ar-^{39}Ar ages, keyed to sample locations within the DHB, are shown in figure 5. Argon isotope spectra and associated data are found in table 2, which is available from *The Journal of Geology* free of charge upon request. Samples are from four localities; however, samples were taken from several different fabrics contained within each outcrop. Hornblende plateau ages fall within two well-defined groups, regardless of the crosscutting relationships seen in the field. One age cluster, around 941–944 Ma, is seen only in outcrops A2, A4, and 87 at the northern tip of the map view of the DHB. The second cluster, found in every sampled outcrop of the

Table 1. Assemblages and Textures of Dana Hill Body Samples

Sample	Outcrop location	General assemblage	Textural description
CR-2A2	A4	bt-ilm-plag-scap-amph	Major mylonite
CR-9A4	A4	px-amph-ilm-bt-plag	Cumulus texture
CR-6A4	A4	plag-amph-chl (late)	Cm-wide shear
CR-12A4	A4	cpx-sph-plag-amph	Amphibole vein
DH2-8	A4	amph-plag	Amphibole vein
DH2-6a	A4	amph-plag-sph	Cm-wide shear
CR-7A4	A4	plag-amph-sph	Major mylonite
DH2-7	A4	amph-plag-sph	Cm-wide shear
CR7-DH1	DH	bt-amph-plag-scap	Cm-wide shear
CR1-DH1	DH	plag-amph-ilm	Cm-wide shear
CR3-87	87	ilm-mag-plag-amph-scap	Amphibole vein
H87-5b	87	chl-trem-relict plag, amph	Breccia
DHR98-1	RW	hbl-trem-plag	Amphibole vein
RWH1	RW	plag-scap-amph-sph	Amphibole vein
RWS3C	RW	plag-amph-scap-px-ep-ilm	Major mylonite
EA1	RW	plag-amph-scap-sph-bt	Amphibole vein
RWS1	RW	plag-scap-amph	Amphibole vein

Note. Abbreviations: bt = biotite, ilm = ilmenite, plag = plagioclase, scap = scapolite, amph = amphibole, px = pyroxene, cpx = clinopyroxene, mag = magnetite, chl = chlorite, sph = titanite, trem = tremolite, ep = epidote.

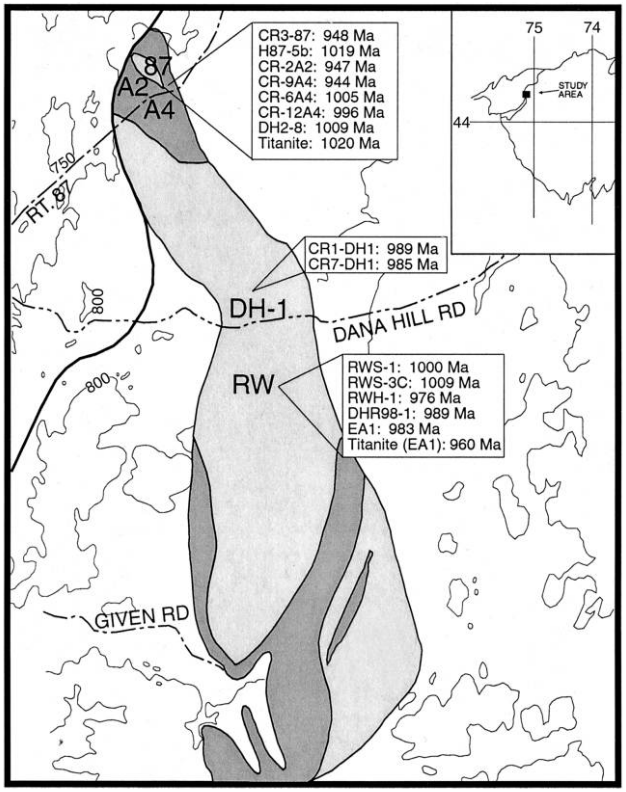

Figure 5. Map of Dana Hill body (heavy black line represents Carthage-Colton boundary to the west). Outcrop locations and ages from each outcrop are indicated. Plateau ^{40}Ar-^{39}Ar ages are indicated, as well as titanite ages for each outcrop. Dark gray indicates the foliated facies of the Dana Hill metagabbro, while light gray indicates the mapped ophitic facies (after Hall 1984).

DHB, is ca. 1000 Ma (age ranges from 973 to 1010 Ma with most ages close to 1000 Ma).

Titanite. The results from 17 titanite analyses are given in table 3 and figure 6. All titanites from the DHB, regardless of sample location, have been dated at 1020 Ma. It is important to note that titanite-bearing assemblages were found in only part of the DHB. The northern outcrops A4 and A2 yielded several samples that were titanite bearing, and titanite grains were contained in crosscutting fabrics. However, outcrops 87, DH-1, and RW, all of which yielded hornblendes suitable for analysis, did not contain titanite. In addition, titanite grains were not available from hornblende-bearing samples that clustered at ca. 945 Ma. Titanites in the DHB were available only from samples that yielded hornblende ages clustering at 1000 Ma. Except for a titanite from a highly sheared amphibole vein (EA1), all titanites from the DHB are concordant (fig. 6). Some titanite grains were also analyzed from the adjacent Adirondack Lowlands and Highlands to characterize further the timing of high-grade metamorphism in these areas and as a comparison to ages found in the sheared DHB. An age of 1150 Ma was found in the Adirondack Lowlands (similar to other ages reported in the vicinity) and ages of ca. 1060–1080 Ma were found in samples from the Adirondack Highlands (fig. 6).

Discussion

Comprehensive geochronologic data show that metamorphism is common to this entire region during the Elzevirian Orogeny from 1150 to 1170 Ma. Explanation of the absence of Ottawan-aged metamorphism at ca. 1050 Ma in the Adirondack Lowlands, despite its prevalence in the adjacent Highlands, and in the western portion of the MB, has been a continuing debate in Grenville geology. Two current hypotheses are that the CCSZ represents the trace of a composite reverse/normal fault and that the CCSZ represents a major suture juxtaposing two terranes that were separated by a small ocean basin during the ca. 1050-Ma Ottawan metamorphism. Using new constraints on the temporal evolution of the shear zone, we will describe two scenarios discussed in the literature (e.g., Mezger et al. 1992) and propose a third scenario for the evolution of the CCSZ.

Composite Reverse/Normal Fault. This scenario suggests that the Adirondack Lowlands escaped 1050-Ma metamorphism, present in all areas of the MB except the Frontenac/Lowlands region, by being positioned at higher crustal levels during the event. In this scenario, granulite-facies metamorphism was due to basaltic underplating combined with tectonic thickening. However, since the Frontenac Lowlands and Highlands terrane were at broadly similar *PT* conditions during the earlier 1150-Ma event, is likely that they were at similar crustal levels. One interpretation is that the Lowlands were thrust over the Highlands after the 1150-Ma metamorphism and before the 1050-Ma metamorphism. In both cases, the zone of shearing is approximately along the trace of the present-day CCSZ. This is supported by the existence of seemingly conflicting shear-sense indicators in the area, some of which show a reverse, top-to-the-east sense of motion while the majority show a northwest-side-down sense of displacement (Hall 1984).

While this is a permissible scenario and provides an explanation for the absence of the 1050-Ma metamorphism in the Lowlands/Frontenac block, it would be, at best, fortuitous to have reverse faulting along the zone and then, later, normal displace-

Table 3. U/Pb Data for Titanite

Sample	U (ppm)	Pb (ppm)	206/204	208/206	207/206	Error	207/235 ratio	Error	206/238 ratio	Error	206/238 age (m.yr.)	207/235 age (m.yr.)	207/206 age (m.yr.)	ρ
CR-12A4	133.35	26.20	5076.1	.2538	.0733	.0001	1.7195	.0075	.1702	.0007	1013	1016	1021	.8997
CR-12A4	142.38	28.68	5702.8	.2855	.0733	.0001	1.7255	.0069	.1708	.0007	1017	1018	1021	.9628
DH2-7	101.75	19.49	3879.9	.2105	.0733	.0001	1.7279	.0062	.1710	.0006	1018	1019	1022	.9507
DH2-7	91.23	17.77	2189.0	.2426	.0732	.0001	1.6957	.1400	.1681	.0139	1002	1007	1018	.9999
CR-7A4	113.18	21.33	562.4	.0926	.0736	.0001	1.7180	.0104	.1692	.0010	1008	1015	1031	.9461
CR-7A4	58.19	10.10	4466.2	.0905	.0733	.0001	1.7323	.0062	.1713	.0006	1019	1021	1023	.9519
DS98-56	14.82	5.54	172.2	.9037	.0757	.0005	1.8716	.0146	.1793	.0008	1063	1071	1087	.6514
DH2-6a	157.26	30.78	2534.4	.2629	.0731	.0001	1.6809	.0063	.1668	.0006	994	1001	1017	.9510
DH2-6a	90.66	18.77	1860.5	.3003	.0731	.0001	1.7184	.0062	.1705	.0006	1015	1015	1017	.9413
SE98-17	39.62	11.21	1340.9	.6887	.0754	.0001	1.8786	.0099	.1807	.0009	1071	1074	1079	.9526
EA1	149.32	38.98	866.3	.7307	.0716	.0001	1.5863	.0058	.1606	.0005	960	965	975	.9107
EA1	185.96	47.52	915.9	.7136	.0715	.0001	1.5684	.0078	.1590	.0007	951	958	973	.9514
BM98-60	78.29	27.41	241.7	.6695	.0795	.0004	2.1576	.0413	.1969	.0036	1159	1168	1184	.9639
BM98-60	96.64	31.19	960.0	.7485	.0784	.0001	2.1267	.0085	.1968	.0007	1158	1158	1156	.9369
BK98-55	329.91	59.32	1731.2	.2769	.0721	.0001	1.4941	.0053	.1504	.0005	903	928	988	.9390
BK98-55	224.21	42.41	2512.9	.2811	.0725	.0001	1.5919	.0294	.1592	.0029	952	967	1001	.9981
SE98-17	39.62	11.21	1340.9	.6887	.0754	.0001	1.8786	.0099	.1807	.0009	1071	1074	1079	.9526

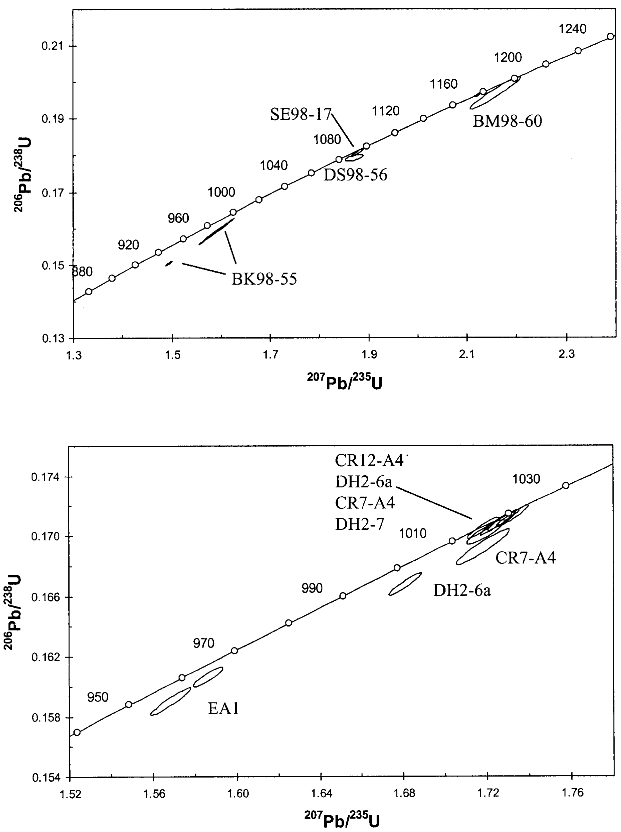

Figure 6. Concordia diagrams for all titanites analyzed in the study. Top panel shows titanites analyzed outside of the Dana Hill body (see fig. 2 for sample locations) in the Adirondack Lowlands and the Highlands. Bottom panel shows titanites analyzed within the Dana Hill body. Concordant titanites cluster at 1020 Ma, with some discordant samples showing slightly younger ages.

ment along the same zone with equal throw. In addition, as observed by Mezger et al. (1992), it seems unlikely that magma generated during a granulite-facies event would stay confined to mid-crustal and lower-crustal levels and not migrate upward to affect shallower crust.

Lateral Separation/Ocean Basin Model. The scenario favored by Mezger et al. (1992) is a lateral separation of the Highlands and Lowlands during the 1050-Ma metamorphism. In this scenario, the Highlands and Lowlands were juxtaposed during the ca. 1150-Ma phase of Elzevirian metamorphism. This juxtaposition continued through emplacement of the Diana syenite, thus explaining its enigmatic relationship with the Highlands and Lowlands. At ca. 1098 Ma (an age obtained by Mezger et al. [1992] from titanites in the southern portion of the CCSZ), a rifting event led to the opening of a small ocean basin between the Highlands and the Lowlands. Thus the two terranes were considered laterally separate during the 1050-Ma event and the Lowlands were protected from high-grade metamorphism during this interval. Later suturing along the CCSZ at a time that was unconstrained rejoined the two terranes. Rift-related volcanics and sediments have never been found in the area, and this interpretation, while possible, also seems unlikely.

Strike-Slip Displacement. We propose, given the new ages and structural relationships obtained in the CCSZ, that the Frontenac/Lowlands block was separated laterally from the Highlands block during the 1050-Ma metamorphism (fig. 7). In this model, all domains that make up the MB were probably in place, yet laterally separate by ca. 1200 Ma. Continued postcollisional shortening allowed for a thick, unstable crust in the Highlands/Lowlands area at ca. 1200 Ma. This led to mantle delamination that caused widespread AMCG emplacement in both the Lowlands and Highlands from 1170 to ca. 1125 Ma (Hanmer et al. 2000; fig. 7). Mantle delamination swept eastward as shown by young ages of AMCG emplacement in the Highlands (McLelland et al. 1996). The unstable crust went through another episode of shortening at the MBBZ at 1050 Ma (Hanmer and McEachern 1993). This shortening was followed closely by oblique slip motion near the core of the orogen at the Highlands/Lowlands boundary. The Lowlands were thrust over the Highlands and lateral motion moved them into their current position (fig. 7). In this model, the Lowlands block was protected from the 1050-Ma metamorphic event in the Highlands by lateral separation combined with some dip-slip displacement. Strike-slip motion is supported by steep fabrics with associated shallow lineations in the DHB, and reverse faulting is supported by reverse shear-sense indicators. Since titanite ages are cooling ages from an upper amphibolite/granulite-facies event (Johnson et al. 2000), we interpret these ages to indicate early activity along the CCSZ at ca. 1040 Ma (using a 2°–3°C m.yr.$^{-1}$ cooling rate [Mezger et al. 1991*a*]).

The timing and nature of this shearing also correlates with transpressional convergence of the Sharbot Lake and Mazinaw domains farther to the west in the MB (Mezger et al. 1993; Busch et al. 1997; fig. 1). Transcurrent deformation has also been observed to the north, in Grenvillian rocks exposed in Québec (e.g., Martignole and Friedman 1998). This indicates that many of the blocks that make up the eastern Grenville were undergoing strike-slip motion during the Ottawan Orogeny. These data collectively suggest that lateral motions

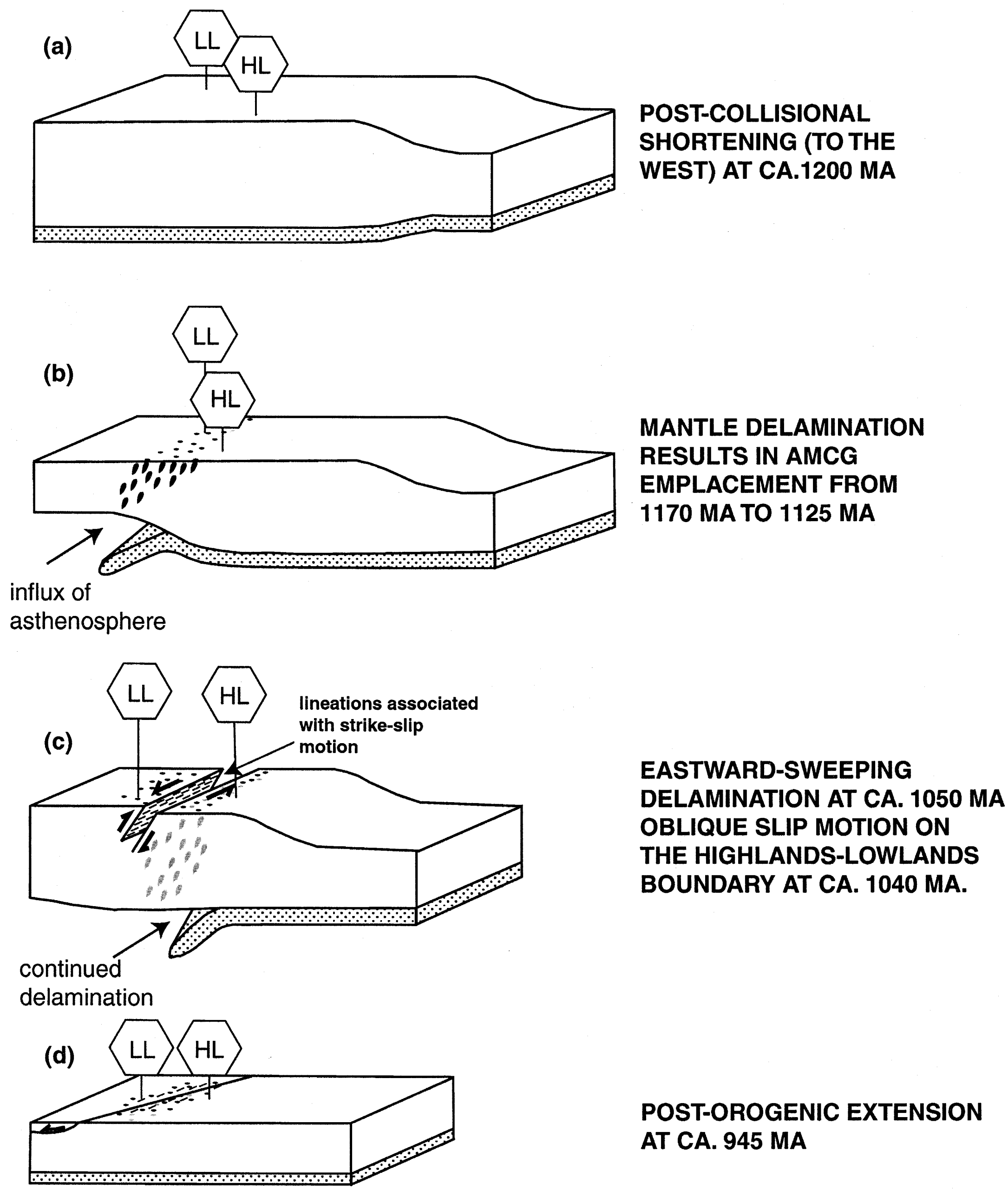

Figure 7. Proposed tectonic scenario for the evolution of the Carthage-Colton Shear Zone (CCSZ). Octagons are markers showing relative locations of Highlands and Lowlands regions. *a*, The Highlands and Lowlands are part of a thickened block at 1200 Ma resulting from postcollisional shortening to the west in the MB. *b*, From 1170 to ca. 1125 Ma, widespread mantle delamination caused AMCG emplacement throughout the Lowlands and in some of the Highlands. Black blobs shown are plutons from this time period. *c*, At 1050 Ma, mantle delamination swept eastward followed by renewed thrusting at the MBBZ. Gray blobs are plutons from this time period. This was closely followed by an oblique slip along the Highlands/Lowlands boundary, which thrusted the Lowlands over the Highlands while at the same time juxtaposing the two into their current lateral configurations. *d*, Postorogenic extension along the CCSZ dropped the Lowlands block and raised the Highlands block. Extension trended to the northeast and was oblique to earlier motion along the Highlands/Lowlands boundary. Continued unroofing exposed the region in its present-day configuration.

among blocks already in place played a major role during the later evolution of the Grenville Orogen. This also supports recent hypotheses that all blocks that make up the Grenville were juxtaposed early in the orogen's history and that later deformation and tectonism affected blocks that were already accreted to the Laurentian margin (e.g., Hanmer et al. 2000). Limiting data on temperature-time paths from the Lowlands and the Highlands require a period of extension along the CCSZ at ca. 940 Ma (Streepey et al. 2000). Therefore, later postorogenic extension occurred along the present-day CCSZ to juxtapose the Highlands and Lowlands at their current structural levels (fig. 7). Hornblende ages of 940–945 Ma within the CCSZ and hornblende and biotite ages in the Highlands and Lowlands constrain the timing of this late extension.

It is important to recognize that early strike-slip displacement and later extension did not necessarily occur along a single fault trace. Rather, the CCSZ is a region of deformation with late extensional shearing oblique to earlier strike-slip deformation (fig. 7). Local fabrics associated with the strike-slip period of deformation trend to the northwest with steep dips, while fabrics associated with extensional motion strike to the north-northeast and dip shallowly to the northwest. This allows for the lithologic continuities across the zone and also clarifies the affinity of the Diana syenite to the Lowlands, despite some lithologic similarity to Highlands rocks.

Recognizing multiple periods of deformation along the CCSZ explains the complexity of field relationships and the difficulty in mapping the zone. While a component of vertical displacement may have been present during the early history of the CCSZ, we conclude that large-scale, lateral displacements within an otherwise coherent southeastern Grenville Province represents the tectonic environment at ca. 1050 Ma.

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